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SLIP OF JOINTS UNDER STATIC LOADS

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STRUCTURAL DIVISION

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EXPLANATORY STATEMENT

Practices in the design of riveted and bolted joints have developed largely from experience and have not always been supported by conclusive experimental data. With this fact in mind, twelve sponsoring organizations instituted the Research Council on Riveted and Bolted Structural Joints, in 1947.

Important among the projects of the Research Council is the study of high-strength bolts in structural joints. The high-strength bolt is a comparatively new type of structural fastener, and its use combines the field economies of bolts with strength greater than that of rivets.

At the Centennial Convention of the ASCE at Chicago, Ill., in 1952, a group of papers were presented describing research that had been done in the field of structural joints, with particular emphasis on study of the high-strength bolt.

These papers are currently being published as Proceedings-Separates and will be distributed over a period of several months beginning in May, 1954. Later, they will be gathered to form a single symposium in the Transactions of the ASCE. The six papers in this group are as follows:

"The Work of the Research Council on Riveted and Bolted Joints," by W. C. Stewart;

"Laboratory Tests of High-Tensile Bolted Structural Joints," by W. H. Munse, J. M. ASCE, D. T. Wright, and N. M. Newmark, M. ASCE;

"Comparative Behavior of Bolted and Riveted Joints," by Frank Baron, M. ASCE, and Edward W. Larson, Jr., J. M. ASCE;

"Slip Under Static Loads of Joints With High-Tensile Bolts," by R. A. Hechtman, A. M. ASCE, D. R. Young, and A. G. Chin and E. R. Savikko, Junior Members, ASCE;

"Fatigue in Riveted and Bolted Single-Lap Joints," by J. W. Carter and K. H. Lenzen, Associate Members, ASCE, and L. T. Wyly, M. ASCE;

"Structural Application of High-Strength Bolts," by T. R. Higgins and E. J. Ruble, Members, ASCE."

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SLIP OF JOINTS UNDER STATIC LOADS

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Synopsis

The primary purpose of this investigation has been to determine the slip of structural steel double-lap joints assembled with high-strength steel bolts when subjected to stresses in the design range and somewhat beyond. The joints were subjected to short-time static loading. Although most of the joints were tested in tension, some were tested in compression and in combined compression and torsion. This paper reports the results of seventy-two tests, which are part of a continuing investigation.

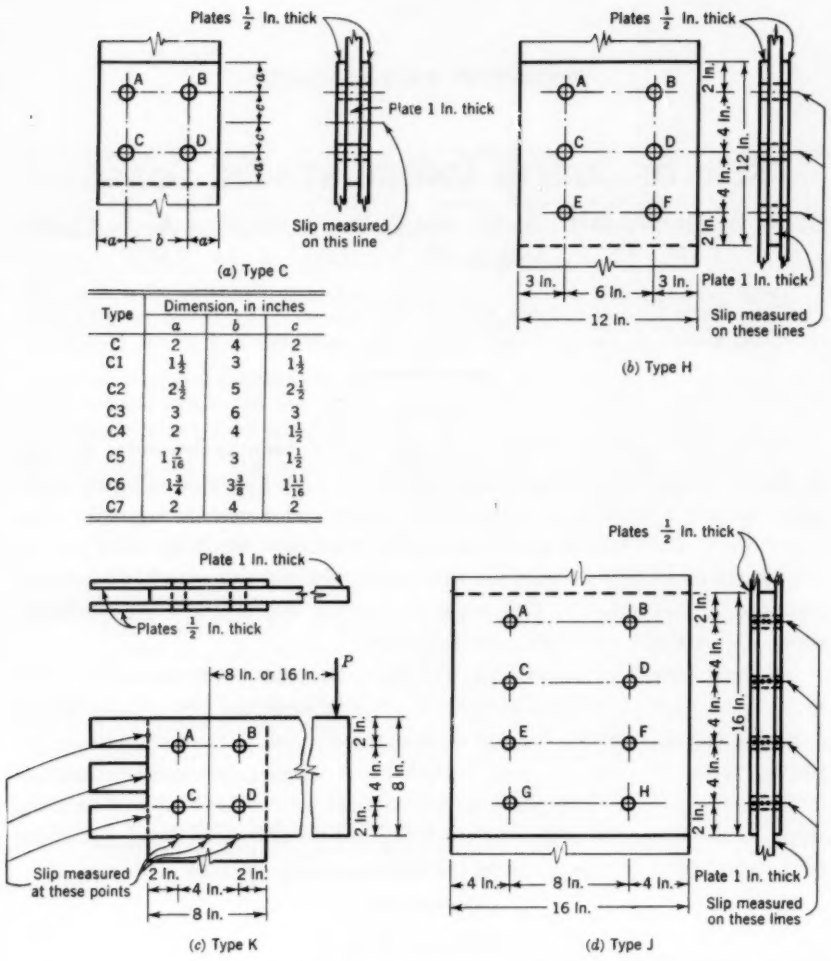
Of the principal factors affecting the slip of the joint, those studied included such dimensional properties as the total faying area, the net cross-sectional area, the thickness of the lap-plates, and the number of rows of bolts in the joints. Other properties studied included bolt tension and surface condition of the faying areas. The joints were compared on the basis of the shearing stress on the bolts, the coefficient of friction and the slip (both developed at the first major slip), and the stress on the net cross-sectional area.

Introduction

The slip of joints assembled with high-strength steel bolts in holes $\frac{1}{16}$ in. larger in diameter than the bolts themselves is resisted initially only by the frictional resistance developed by the normal pressure of the bolts on the faying, or contact, areas between the plates of the joint. In mobilizing this resistance, little slip occurs in a properly designed joint. If the applied load exceeds the initial frictional resistance of the joint, a sudden and appreciable slippage occurs. This point, termed the first major slip, is followed by further slippage of the plates subjected to continued loading until the plates are bearing fully on the bolts.

Three properties are required of a bolted joint designed to resist slip through the frictional resistance developed between the plates:

1. The slip when stresses are within the design range must be small.



Type	Dimension, in inches		
	a	*b*	*c*
C	2	4	2
C1	$1\frac{1}{2}$	3	$1\frac{1}{2}$
C2	$2\frac{1}{2}$	5	$2\frac{1}{2}$
C3	3	6	3
C4	2	4	$1\frac{1}{2}$
C5	$1\frac{7}{16}$	3	$1\frac{1}{2}$
C6	$1\frac{3}{4}$	$3\frac{3}{8}$	$1\frac{11}{16}$
C7	2	4	2

FIG. 1.—DETAILS OF JOINT SPECIMENS

2. The slip when stresses are within the design range should not continue to increase during the life of the structure while the joint resists its applied load.
3. A reasonable margin of safety should be present in the joint with respect to the two foregoing properties.

The first requirement is met if the upper limit of the design range of the joint is less than the stress at the first major slip. To meet the second requirement, it is essential that those properties of a joint which produce frictional resistance are not significantly diminished as time elapses. The proper relation of design stresses to the results of tests of bolted joints assures fulfilment of the third requirement.

The program of tests reported herein was directed toward obtaining data concerning the slip of bolted double-lap structural joints resisting loads up to the load at which the joints slipped into full bearing and at which the bolts began to deform the holes. Special attention was given to the particular shearing stress on the bolts at which the first major slip occurred and to the distance the plates slipped before this point was reached. The phrase "shearing stress on the bolts" is used here in its usual meaning to the structural designer because shear did not actually exist in the bolts until they were bearing on the plates. The average shear on the bolts in these tests was always computed on the basis of the gross cross-sectional area of the bolts. The tension in the bolts was controlled in all tests, the maximum deviation from the desired tension being approximately 3%.

Description of Joint Specimens and Test Methods

Joint Specimens.—The program of tests is given in Table 1. The details of the joints are shown in Figs. 1 and 2. All the specimens were double-lap joints with butt plates 1 in. thick and lap plates ½ in. thick, except for specimen Nos. 80, 81, and 82, which had lap plates $\frac{5}{16}$ in. thick. The high-strength steel bolts used were 1 in. in diameter. The clearance in all bolt holes was $\frac{1}{16}$ in.

TABLE 1.—Program of Tests

Specimen[a]		Lap Plates			Bolts		Faying area (sq in. per bolt)	Nominal bolt tension[d] (kips)	Tension-shear ratio[e]	Loading	
No.	Type	Thickness (in.)	Net area (sq in.)	Surface condition[b]	Type[c]	Number in joint				Type[f]	Eccentricity (in.)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
10–12B	C1	½	3.91	MS	4140	4	18.0	45.0	1.00:0.62	Te	0
13–15B	C	½	5.91	MS	4140	4	32.0	45.0	1.00:0.94	Te	0
16–18	C2	½	7.91	MS	4140	4	50.0	45.0	1.00:1.26	Te	0
19–21	C3	½	9.91	MS	4140	4	72.0	45.0	1.00:1.58	Te	0
31–33	C4	½	5.91	MS	4140	4	28.0	24.0	1.00:0.94	Te	0
37–39	C	½	5.91	MS	4140	4	32.0	36.0	1.00:0.94	Te	0
48–50	C	½	5.91	RL	4140	4	32.0	45.0	1.00:0.94	Te	0
51–53	C	½	5.91	V	4140	4	32.0	45.0	1.00:0.94	Te	0
54–56	C	½	5.91	S	4140	4	32.0	45.0	1.00:0.94	Te	0
57–59	C4	½	5.91	MS	4140	4	28.0	36.0	1.00:0.94	Te	0
63–65	H	½	9.88	MS	4140	6	48.0	42.5	1.00:1.05	Te	0
66–68	J	½	13.88	MS	4140	8	64.0	42.5	1.00:1.10	Te	0
74–76	C	½	5.91	SPR	4140	4	32.0	45.0	1.00:0.94	Te	0
77–79B	C	½	5.88	MS	4140	4	32.0	42.5	1.00:0.94	Te	0
80–82	C7	$\frac{5}{16}$	3.67	MS	4140	4	32.0	42.5	1.00:0.59	Te	0
101–103	C	½	5.88	MS	A 325	4	32.0	42.5	1.00:0.94	Te	0
104–106	C	½	5.88	MS	4140	4	32.0	42.5	1.00:0.94	C	0
107–109	C	½	5.88	MS	A 325	4	32.0	52.0	1.00:0.94	Te	0
119–121	K	½	...	MS	4140	4	32.0	42.5	....	To	8
122–124	K	½	...	MS	4140	4	32.0	42.5	....	To	16
128–130	C6	½	4.75	MS	A 325	4	23.6	42.5	1.00:0.75	Te	0
131–133	C5	½	3.75	MS	A 325	4	17.3	42.5	1.00:0.60	Te	0
137–139	C6	½	4.75	MS	A 325	4	23.6	52.0	1.00:0.75	Te	0

[a] Types of specimens are detailed in Fig. 1. [b] Surface conditions are described as follows: MS indicates mill-scale surface, wire-brushed, and cleaned with carbon tetrachloride to dissolve grease and oil. RL indicates wire-brushed, cleaned mill scale, covered with one coat of red lead paint. Paint aged 30 days before assembly. V indicates wire-brushed, cleaned mill scale, covered with one coat of fast-drying varnish. Varnish aged a week before assembly. S indicates that mill scale was completely removed by sandblasting. Surface was cleaned with carbon tetrachloride. SPR indicates that holes in the lap plates were subpunched ¹³⁄₁₆ in. in diameter and reamed. Holes in the center plate were drilled ¹³⁄₁₆ in. in diameter and reamed. Lap plates were slightly dished around the holes by punching. [c] Bolts that met either Society of Automotive Engineers (SAE) 4140 or American Society for Testing Materials (ASTM) A 325 specifications. [d] Specimen Nos. 107 to 109 and 137 to 139 had bolt tension 10% greater than the elastic proof load. [e] The ratio of the average tensile stress or compressive stress on the net cross-sectional area of the lap plates to the average shearing stress on the gross cross-sectional area of the bolts. [f] The symbol, Te, denotes tension; C, compression; and To, torsion.

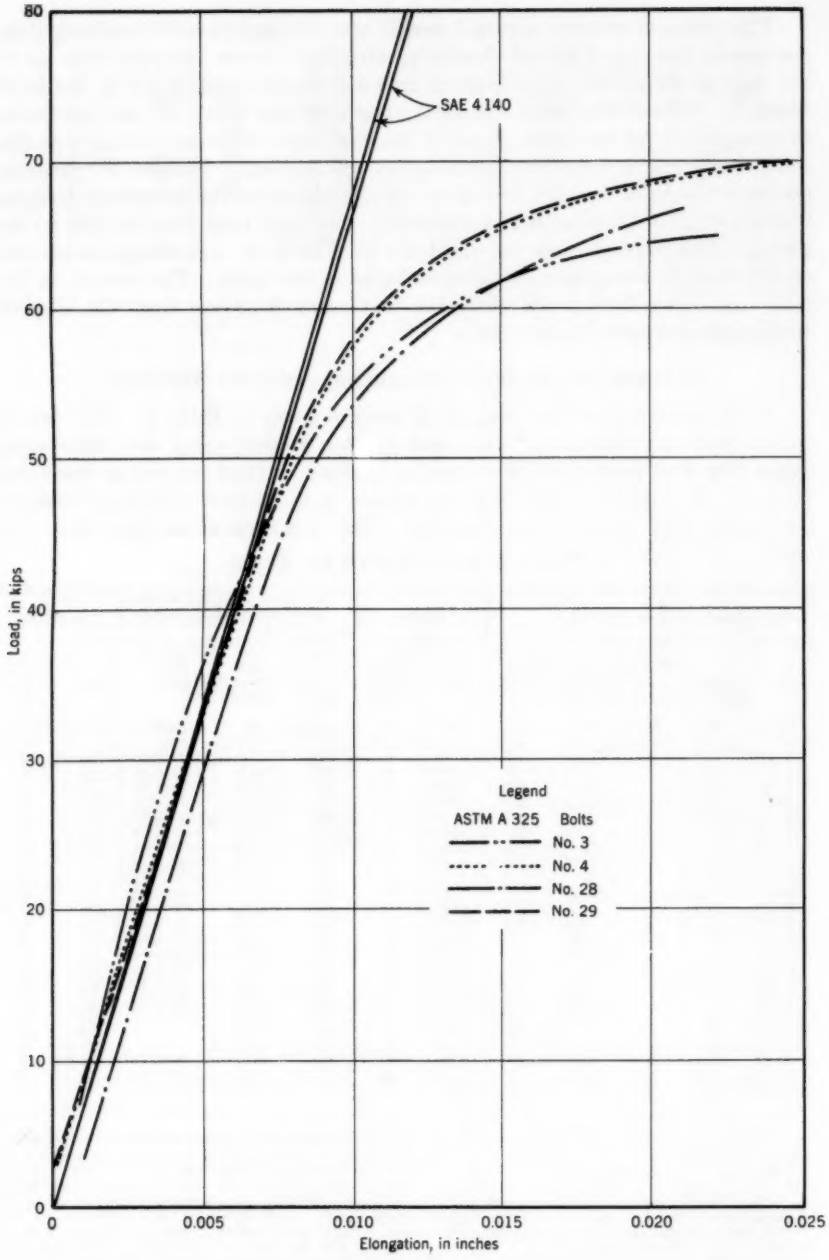


FIG. 2.—LOAD-ELONGATION CURVES FOR TYPICAL BOLTS OF 1-IN. DIAMETER

The edges of the joints were milled to the specified width. The plates were then clamped in the same positions in which they were to be tested, and the holes were drilled through all the plates in one operation. This procedure assured alinement of the holes. The surface condition given the faying areas of the joints before assembly is described in Table 1. The burred edges of the drilled holes were smoothed. The plates were then assembled with tight-filling taper pins to aline the holes. The bolts were placed with one washer under the head and one under the nut and were tightened to an elongation corresponding to the desired bolt tension as determined in the calibration test.

The bolt holes in the lap plates of the three specimens with subpunched and reamed holes were punched $\frac{13}{16}$ in. in diameter and reamed to the proper size with the plates assembled in the same manner as the joints with drilled holes. The butt plates of these joints had drilled holes. As the punching slightly "dished" the plates around the holes, the specimens were assembled so that the dished side of one lap plate was bearing on the butt plate, and that of the other lap plate was turned away from it.

Properties of Plates, Bolts, and Washers.—The average tensile properties of the semi-killed, plain-carbon structural steel meeting specification A 7-52T of the American Society for Testing Materials (ASTM),[5] from which the joints were fabricated, are given in Table 2. These properties were determined by testing two standard (ASTM) flat coupons from each plate. If more than one plate of a particular thickness was used, only the maximum and minimum properties are listed in this table.

[5] "Specifications for Steel for Bridges and Buildings (A 7–52T)," A.S.T.M., 1952.

Two types of bolts were used—a type made of heat-treated steel meeting specification 4140 of the Society of Automotive Engineers (SAE),[6] and a type meeting ASTM specification A 325-52T.[7] Typical load-elongation curves for these two types of bolts are shown in Fig. 2. Every bolt used was in-

[6] "1951 SAE Handbook," Soc. of Automotive Engrs., 1951, p. 42.

[7] "Specifications for Bolts and Studs with Suitable Nuts and Plain Washers, Quenched and Tempered (A 325–52T)," A.S.T.M., 1952.

TABLE 2.—TENSILE PROPERTIES OF STEEL PLATES

Plate thickness,[a] in inches	Upper yield point, in pounds per square inch	Ultimate strength, in pounds per square inch	Percentage elongation in 8 in.	Reduction of area, in percentage
$\frac{7}{16}$	45,400	68,200	26.5	52.9
$\frac{1}{2}$	36,600 to 40,100	58,100 to 62,100	24.9 to 31.0	49.0 to 57.2
1	32,800 to 36,000	59,600 to 63,600	27.3 to 31.2	44.9 to 56.3

[a] Data from one plate $\frac{7}{16}$ in. thick, six plates $\frac{1}{2}$ in. thick, and three plates 1 in. thick.

dividually calibrated in tension at its exact grip to obtain the relation between bolt tension and elongation. As the bolt tensions used in most of the joints were at, or just below, the elastic proof load of an A 325 bolt, the SAE 4140 bolts with a higher proportional limit were used in most of the joints to assure that the bolts would not need to be recalibrated after each test because of any slight overstressing of the bolts during tightening or testing. The A 325 bolts

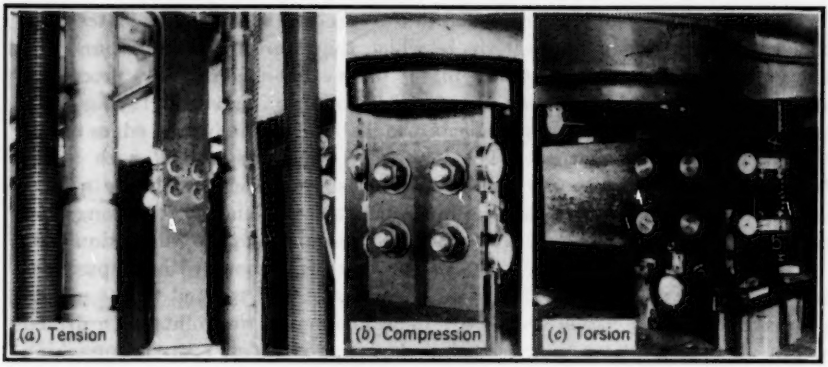


FIG. 3.—JOINTS READY FOR TESTING

were reused in subsequent tests only when their initial tension was less than their elastic proof load. The washers were $\frac{3}{16}$ in. thick, and their surfaces were carburized $\frac{1}{32}$ in. deep.

Method of Testing.—The tension joints were tested in hydraulic testing machines having capacities of either 300,000 lb or 2,400,000 lb. The arrangement for testing a tension joint is shown in Fig. 3(*a*); a compression joint is shown in Fig. 3(*b*); and in Fig. 3(*c*) is indicated the arrangement for testing a torsion joint. The load was applied slowly, and the dials were read at frequent intervals and immediately after each sudden slippage. The eccentricity of the torsion joints was measured from the loading point to the center of gravity of the bolt group. On completion of the tests, the residual bolt tension (the bolt tension after testing) was determined by the relaxation method.

The test section of a specimen was sometimes used a second time. In these cases, the lap plates were interchanged without rotation. This placed on the outside of the joint the surfaces that had already been tested, whereas the bolt holes formed by one operation of the drill were kept together. The surfaces of the center plate were thus tested twice, although the surfaces of the lap plates were tested only once. This dual use of test sections did not seem to affect the results significantly. Specimens were not used a second time if the first test had elongated the holes by more than 0.003 in.

SLIP IN TYPICAL BOLTED TENSION JOINTS

The results of each test were plotted in the form of curves relating shear and slip, in which the average shear stress on the gross area of the bolts was compared with the average of the slips measured on the two edges of the joint. Typical shear-slip curves for tension joints are shown in Figs. 4 and 5. These indicate two distinct patterns of behavior—that for joints with mill-scale faying surfaces, and that for joints with painted faying surfaces. Further related information appears in Fig. 1 and Table 1.

Figs. 4, 5(*a*), and 5(*d*) are shear-slip curves for joints with mill-scale faying

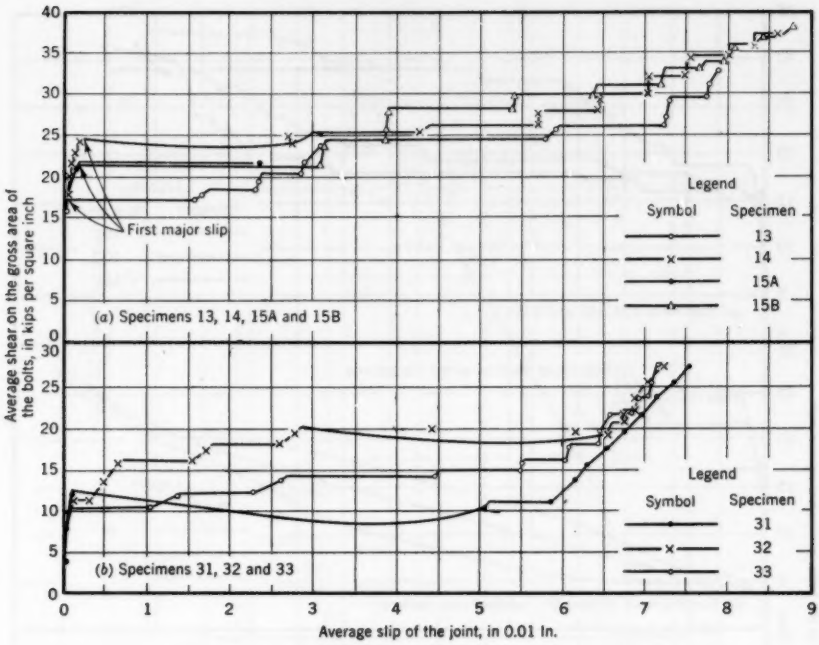


FIG. 4.—COMPARISON OF NOMINAL SHEAR ON THE BOLTS AND AVERAGE SLIP OF THE JOINTS

surfaces. When load was applied to a specimen of this type, there was at first no large slip. A load was eventually reached at which the initial frictional resistance to slip was overcome, and the plates slipped with extreme rapidity. This first large and sudden slip is referred to as the "first major slip" and is so marked in Fig. 4(*a*). As the result of several further cycles of load and slip, the bolts were brought into full bearing on the plates. Thereafter, the increment of load required to produce a given amount of slip was greater than before because the bolts were bearing upon the plates. The test was halted when full bearing was attained.

If a design involves the requirement that slip be held to a minimum in order to maintain moment continuity in a connection or to prevent undesirable deflection of the structure, the part of the shear-slip curves below the point of first major slip would become the operating range of the joint. In other types of connections, slip into full bearing would be entirely permissible. Full bearing in these tests occurred when the average slip was 0.062 in.

Specimens with varnish or red lead paint on the faying surfaces had a relationship between shear and slip much different from that of the tests previously described. Instead of slipping suddenly at various increments of load and then maintaining that amount of slip (as did the joints with mill-scale faying areas), the joints with painted faying surfaces slipped slowly and continuously even with small loads. When resisting a constant load, joints of the latter type slipped slowly, the rate of slip decreasing with time. When the

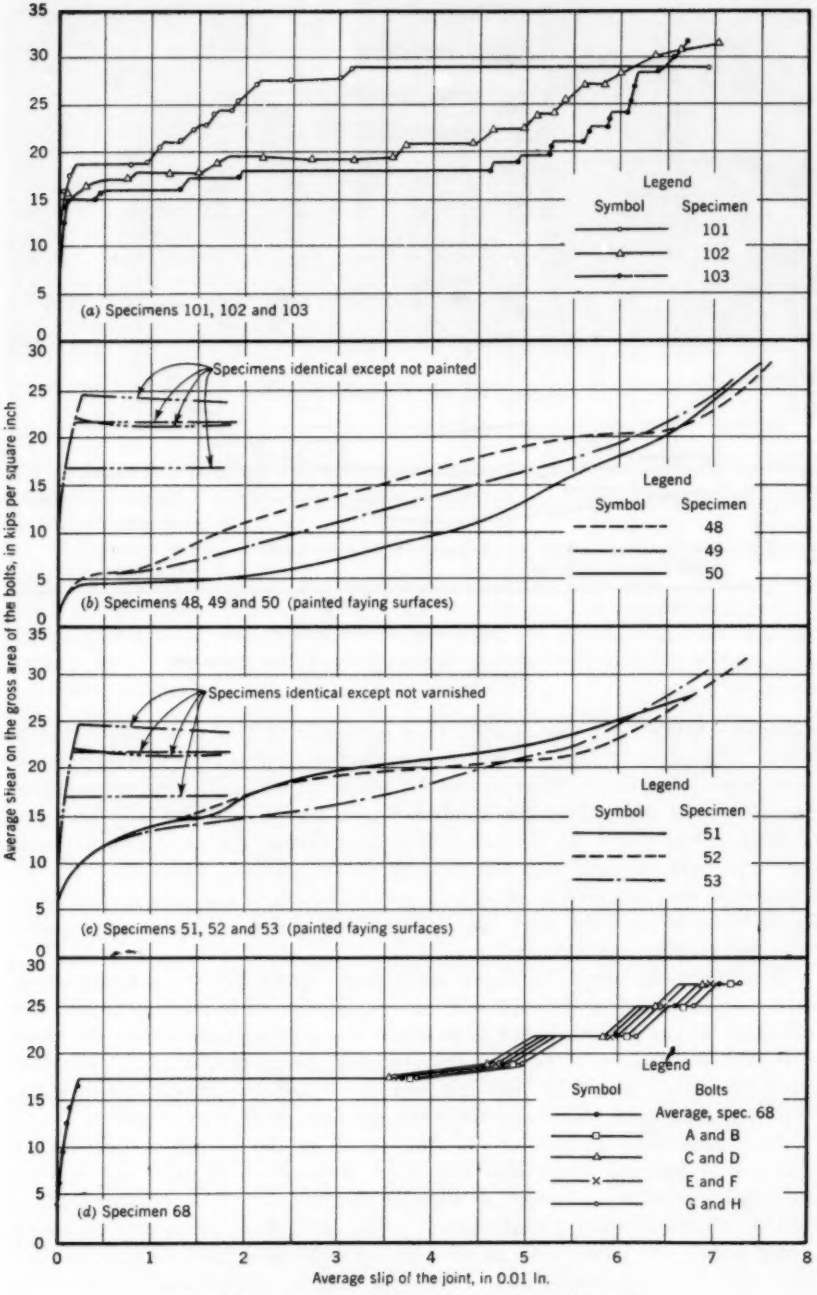


FIG. 5.—COMPARISON OF NOMINAL SHEAR ON THE BOLTS AND AVERAGE SLIP OF THE JOINTS

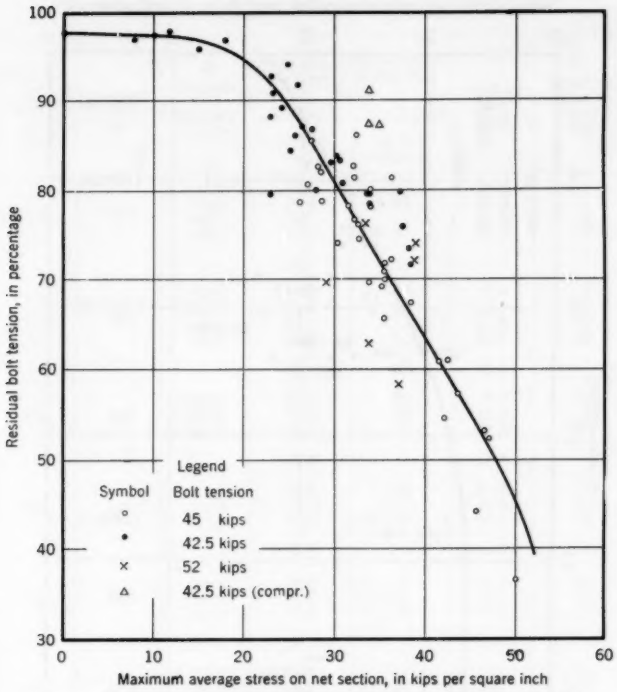


FIG. 6.—MAXIMUM AVERAGE STRESS ON NET CROSS-SECTIONAL AREA COMPARED WITH RESIDUAL BOLT TENSION

time rate of slip at any one load decreased to an average of 0.0001 in. per min in these tests, the slip was read on the dial indicators. This method of slow loading minimized the influence of the operator of the testing machine on the shape of the shear-slip curves and gave a more accurate picture of the behavior of such a joint in a structure.

The more important data of all the tests are summarized in Table 3. The average bolt tension listed in Col. 4 was the average of the measured values. The term "first slip" refers to the first major slip. For torsion specimens, the eccentricity is designated as e.

RESIDUAL BOLT TENSION RELATED TO JOINT STRESS

A comparison of the maximum average tensile stress (P/A) occurring on the net section of the lap plates during the test and the residual bolt tension after removal of the load from the joint, in percentage of the initial bolt tension, is shown in Fig. 6 for the tension and compression joints. The results indicated that an essentially linear relationship existed between the maximum stress on the net cross section and the residual bolt tension when the former was greater than approximately 20 kips per sq in. As the stress increased from 20 kips per sq in. to 50 kips per sq in., the residual bolt tension decreased from 94% to approximately 45% of the original bolt tension. The three compression joints, specimen Nos. 104 through 106, developed residual bolt tensions from 10% to 20% greater than similar joints tested in tension. Over-

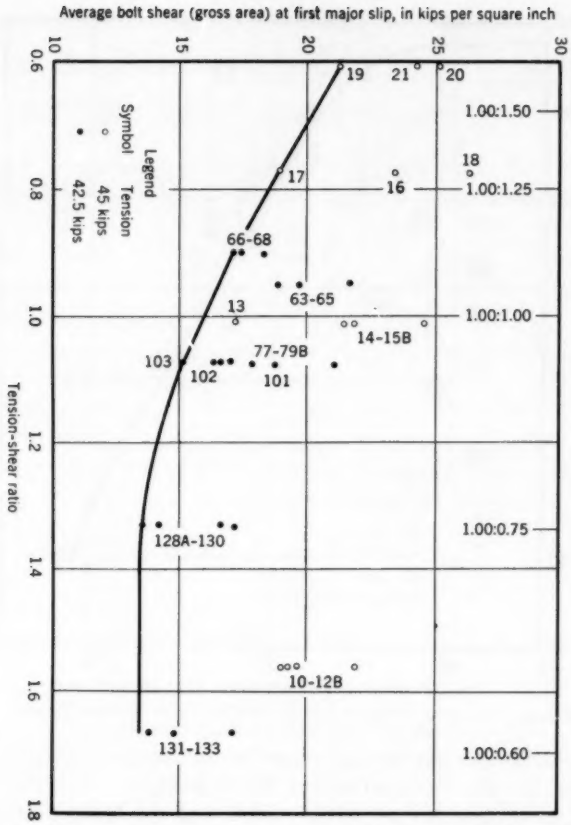


FIG. 7.—COMPARISON BETWEEN AVERAGE BOLT SHEAR AT FIRST MAJOR SLIP AND THE TENSION-SHEAR RATIO

tightening the A 325 bolts to a tension 10% above the elastic proof load of the bolt caused the same proportionate reduction in the residual bolt tension as was found for the 42.5-kip bolt tension.

The residual bolt tension varied little when the maximum tensile stress on the net cross section varied from 0 to 15 kips per sq in.; the residual bolt tension for this range of maximum stress was approximately 97% of the initial value. None of the joints having values of stress on this horizontal part of the curve had reached first major slip; all the joints having values of stress on the sloping part of the curve had undergone their first major slip, and most had slipped into bearing on the bolts.

EFFECT OF TENSION-SHEAR RATIO AND FAYING AREA ON AVERAGE BOLT SHEAR

Tension-Shear Ratio.—The data summarized in Table 3 indicate that the tensile stress on the net cross section at the first major slip was often a factor in determining the potential frictional resistance of a tension joint. This fact is indicated in Fig. 7, which is a comparison between the minimum average shear

TABLE 3.—Summary of Test Results[a]

Specimen No.	Specimen Type	Surface condition[b]	Average bolt tension, in kips	Average Bolt Shear[c], in Kips per Square Inch		P/A at first slip[d]	Total slip prior to first slip[e]	Coefficient of friction at first slip[f], in %
				At first slip	At full bearing			
10	C1	MS	45.1	19.7	25	30.8	9	33
11			44.8	19.4	25	30.2	11	33
12A			45.1	19.2	....	30.0	9	32
12B			45.1	21.9	27	34.3	13	37
Avg				20.1				34
13	C	MS	45.1	17.2	26	17.8	5	29
14			45.3	24.7	28	25.5	22	42
15A			44.0	21.6	....	22.3	10	36
15B			44.8	22.0	31	22.7	13	37
Ayg				21.4		22.1		36
16	C2	MS	44.7	23.3	33	17.9	14	40
17			44.6	18.8	32	14.5	10	32
18			44.4	26.4	38	20.3	30	45
Avg				22.8		17.6		39
19	C3	MS	44.9	21.6	33	13.3	17	37
20			44.6	25.2	32	15.5	10	43
21			44.9	24.3	39	14.9	18	41
Avg				23.7		14.6		40
31	C4	MS	24.2	12.5	15	12.9	14	39
32			24.2	11.6	19	12.0	15	37
33			23.8	10.5	19	10.8	6	34
Avg				11.5		11.9		37
37	C	MS	35.7	15.9	24	16.4	21	34
38			36.5	20.2	24	20.7	18	42
39			35.4	16.2	24	16.7	7	35
Avg				17.4		17.9		37
48	C	RL	44.6	....	21	....	....	....
49			44.9	....	....	....	....	....
50			45.0	....	....	....	....	....
51	C	V	44.4	....	....	....	....	....
52			45.5	....	....	....	....	....
53			44.8	....	....	....	....	....
54	C	S	45.6	26.2	25	27.0	16	44
55			44.7	22.5	26	23.2	19	38
56			44.7	34.6	33	35.6	30	59
Avg				27.8		28.6		47
57	C4	MS	35.8	16.9	25	17.4	10	36
58			37.3	18.6	27	19.2	21	38
59			36.8	18.1	25	18.6	12	37
Avg				17.9		18.4		37
63	H	MS	42.4	19.7	27	18.8	35	37
64			42.7	18.9	24	18.0	23	35
65			42.5	21.7	24	20.7	40	40
Avg				20.1		19.2		37
66	J	MS	42.4	18.2	25	16.5	29	34
67			42.4	17.2	23	15.6	29	32
68			42.6	17.3	25	15.7	33	32
Avg				17.6		15.9		33

[a] The term "First Slip," as used in this table, refers to the first major slip. [b] Definitions of code letters are to be found in Table 1. [c] In torsion joints, this is the shear stress on bolts carrying maximum stress. [d] The symbol P represents axial force, and A represents the cross-sectional area. [e] In inches, to be multiplied by 10^{-3}. [f] In torsion joints, this is the coefficient of friction for bolts carrying maximum stress.

TABLE 3.—(*Continued*)

Specimen		Surface condition[b]	Average bolt tension, in kips	Average Bolt Shear[c], in Kips per Square Inch		P/A at first slip[d]	Total slip prior to first slip[e]	Coefficient of friction at first slip[f], in %
No.	Type			At first slip	At full bearing			
74	C	SPR	44.9	20.6	26	21.2	13	35
75			44.6	19.3	30	19.9	9	33
76			45.4	20.1	28	20.7	15	34
Avg				20.0		20.6		34
77	C	MS	42.4	16.7	27	17.9	6	31
78			42.6	17.0	28	18.2	8	31
79A			42.6	21.2	29	22.6	9	39
79B			42.2	17.9	27	18.6	9	33
Avg				18.2		19.3		34
80	C7	MS	42.3	20.0	24	34.3	29	37
81			42.4	15.3	....	26.3	10	29
82			42.6	18.6	26	31.9	11	34
Avg				18.0		30.8		33
101	C	MS	42.2	18.8	29	20.1	15	35
102			42.2	16.5	30	17.6	9	31
103			42.0	15.1	29	16.2	6	28
Avg				16.8		18.0		31
104	C	MS	42.4	20.0	30	21.3	10	37
105			42.2	20.4	30	21.8	12	38
106			42.6	20.4	29	21.8	7	38
Avg				20.3		21.6		38
107	C	MS	52.0	19.9	30	21.2	13	30
108			52.7	18.5	30	19.8	11	28
109			52.0	16.3	28	17.4	11	24
Avg				18.2		19.5		27
119	K $e = 8$ in.	MS	42.5	23.2	....	....	....	43
120			42.5	27.8	....	....	....	51
121			42.2	24.2	34	....	....	45
Avg				25.1				46
122	K $e = 16$ in.	MS	42.8	21.6	28	....	....	40
123			42.8	21.2	33	....	....	39
124			42.3	22.3	30	....	....	41
Avg				21.7				40
128A	C6	MS	41.4	16.6	22	21.9	7	32
128B			42.6	14.1	23	18.6	42	26
129			42.2	13.4	19	17.7	48	24
130			42.3	17.1	18	22.6	10	32
Avg				15.3		20.2		29
131	C5	MS	42.6	17.1	22	28.7	27	32
132			42.3	13.7	23	23.0	9	26
133			43.0	14.8	23	24.7	8	27
Avg				15.2		25.5		28
137	C6	MS	52.1	21.8	29	28.9	36	33
138			52.4	22.3	23	30.3	18	34
139			52.5	21.3	29	28.1	13	33
Avg				21.8		29.1		33

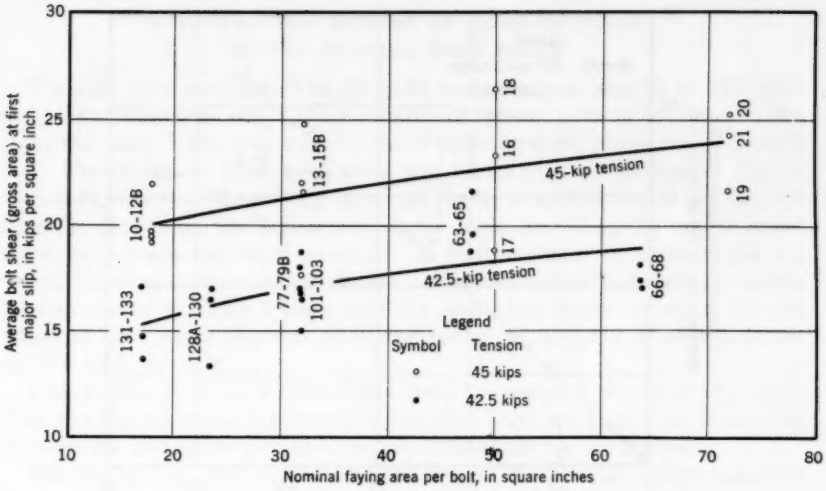


FIG. 8.—COMPARISON BETWEEN AVERAGE BOLT SHEAR AT FIRST MAJOR SLIP AND THE FAYING AREA PER BOLT

developed on the bolts at first major slip and the tension-shear ratio for tension joints with different net cross-sectional areas. Plotted values in Fig. 7 are identified by the applicable specimen numbers. An increase in the tension-shear ratio corresponds to a decrease in the net cross-sectional areas. As the tension-shear ratio increased, the average shear on the bolts at first major slip decreased sharply. For a tension-shear ratio of 1.33 (or 1.00:0.75, as it is more commonly expressed by the designer), the minimum average shear on the bolts at first major slip was approximately 13,500 lb per sq in.

Because the upper yield point of the plates used in these joints ranged from 32,800 lb per sq in. to 40,000 lb per sq in. and because a stress concentration factor of approximately 3 would exist adjacent to the bolt holes, yielding of the plates in the region of the bolt holes was to be expected when design stress was exerted on the net cross-sectional area. This yielding decreased the thickness of the plates around the bolt holes. The contraction relaxed the tension in the bolts as shown in Fig. 6 and thereby reduced the normal pressure on the faying areas, which produced the frictional resistance.

Faying Area.—Fig. 8 is a comparison between the average shear on the bolts at first major slip and the nominal faying area per bolt, which is the total faying area of the joint divided by the number of bolts. All these specimens had mill-scale faying areas (prepared as described in the footnote to Table 1). The specimen numbers identify plotted values in Fig. 8. The joints with the larger faying areas developed somewhat higher values of the shear at first major slip than did those with the smaller faying areas. The relationship was not linear, the values of the shear becoming almost constant as the faying area increased. As the joints with the smaller faying areas also had the smaller net cross-sectional areas, the effect of higher stresses in reducing the shear at first major slip (as shown in Fig. 7) must be considered. It seems reasonable to conclude that the size of the faying area alone had no significant effect on the bolt shear developed at first major slip.

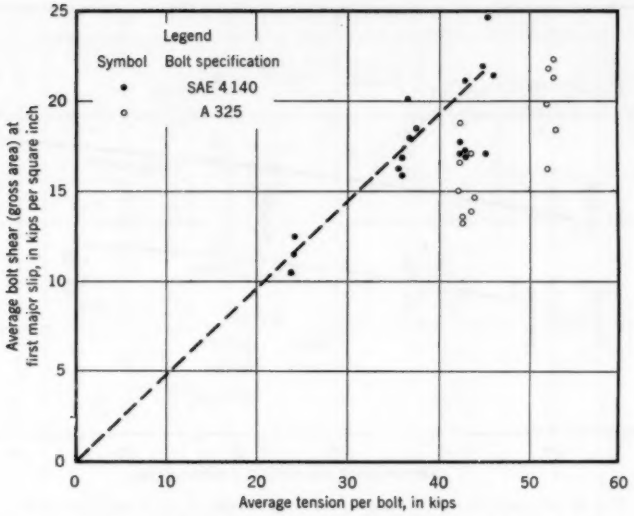


FIG. 9.—COMPARISON BETWEEN THE AVERAGE SHEAR ON THE BOLTS AT FIRST MAJOR SLIP AND THE INITIAL BOLT TENSION

Faying area, as previously defined, is the area of overlap between the butt plate and the lap plates. The actual area of contact between the plates was much smaller than the nominal faying area; an examination of the joints after testing showed that the actual areas of contact were concentrated around the immediate vicinity of the bolts.

EFFECT OF BOLT TENSION ON AVERAGE BOLT SHEAR AT FIRST MAJOR SLIP

Fig. 9 is a comparison among similar specimens with bolt tensions of 24 kips, 36 kips, 42 kips, 45 kips, and 52 kips per bolt. All the joints in this phase of the investigation had mill-scale surfaces and drilled holes. For the bolt tensions of 24 kips, 36 kips, and 45 kips, only the SAE 4140 bolts were used in the test joints. Both SAE 4140 and A 325 bolts were used for the specimens with the 42.5-kip tension. All bolts with the 52-kip tension were of the A 325 type, tightened to a stress 10% greater than their elastic proof load.

The results in Fig. 9 showed that the average bolt shear developed at first major slip was linearly related to the bolt tension for values of the bolt tension less than 36 kips. Increasing the bolt tension beyond approximately 36 kips caused no significant increase in the resistance to slip of the bolted joints, so long as the average stress on the net section at first major slip was less than between 16 kips per sq in. and 18 kips per sq in., or less than half the upper yield point of the plate steel. On the contrary, if the minimum stress on the net section at first major slip was greater than between 16 kips per sq in. and 18 kips per sq in., increasing the bolt tension improved the frictional resistance of the joints; the net-section stress for a balanced design with a tension-shear ratio of 1.00:0.75 would be in this higher range.

Effect of the Number of Rows of Bolts on the Average Bolt Shear

The data from specimen Nos. 63 to 68 and specimen Nos. 77 to 79B were used to investigate the effect of the number of rows of bolts in the joint on the slip of the joint. The number of rows of bolts in these joints varied from 2 to 4. The design of these specimens was based on the findings of Fig. 8, which indicated that the average shear on the bolts at first major slip did not appear to depend on the faying area of the joint, providing the tensile stress on the net section was kept constant. It was necessary to increase the net cross-sectional area of these joints as the number of rows of bolts was increased. The test results in Table 3 show that the maximum tensile stress on the net section at first major slip was 22.6 kips per sq in. and the minimum stress was 15.6 kips per sq in.

A shear-slip curve for a typical test from this series is shown in Fig. 5(*d*). When the slip curves of the individual rows of bolts are examined, it may be seen that the first major slip occurred simultaneously on all the bolts.

The plot in Fig. 10(*a*) shows a comparison of the average results obtained from each group of identical joints. Bolts were arranged as shown in Fig. 1. All specimens had mill-scale surfaces. As the number of rows of bolts increased from 2 to 4, the behavior of the joints was essentially the same. For a longer joint, the exterior bolts might slip before the load could be effectively transferred to the interior bolts. Tests of joints with ten and sixteen rows of bolts are being planned (1952).

Effect of the Lap-Plate Thickness on the Average Bolt Shear

The effect of lap-plate thickness on slip was determined by comparing the results obtained from specimen Nos. 80 to 82, which had lap plates $\frac{5}{16}$ in. thick, with those from specimen Nos. 77 to 79B, which had $\frac{1}{2}$-in.-thick lap plates. The average nominal shear on the bolts at first major slip was of the same magnitude for both thicknesses of lap plates; at full bearing the nominal shear on the bolts was less for the joint with the $\frac{5}{16}$-in.-thick lap plates, being 25 kips per sq in. as compared to 28 kips per sq in. for the joints with $\frac{1}{2}$-in.-thick lap plates. The average coefficient of friction at first major slip was 0.33 for the joints with lap plates $\frac{5}{16}$ in. thick and 0.34 for the joints with lap plates $\frac{1}{2}$ in. thick. Thus, for the types of joints tested, there was no apparent difference in the coefficient of friction.

It would seem that the joint with the thinner lap plates would slip at a smaller load because the lap plates would yield at a smaller load. However, it was found that the $\frac{5}{16}$-in.-thick lap plates had an average yield strength of 45.4 kips per sq in. as compared to 38.5 kips per sq in. for the $\frac{1}{2}$-in.-thick plates. Thus, the possible effect of the greater tensile stress on the net section of the $\frac{5}{16}$-in.-thick lap plates was countered in these tests by the higher yield strength of the plate.

Effect of the Surface Condition of Faying Areas

In tests to determine the effect of the surface condition of faying areas on the slip of bolted joints, type C specimens (Fig. 1) were used exclusively.

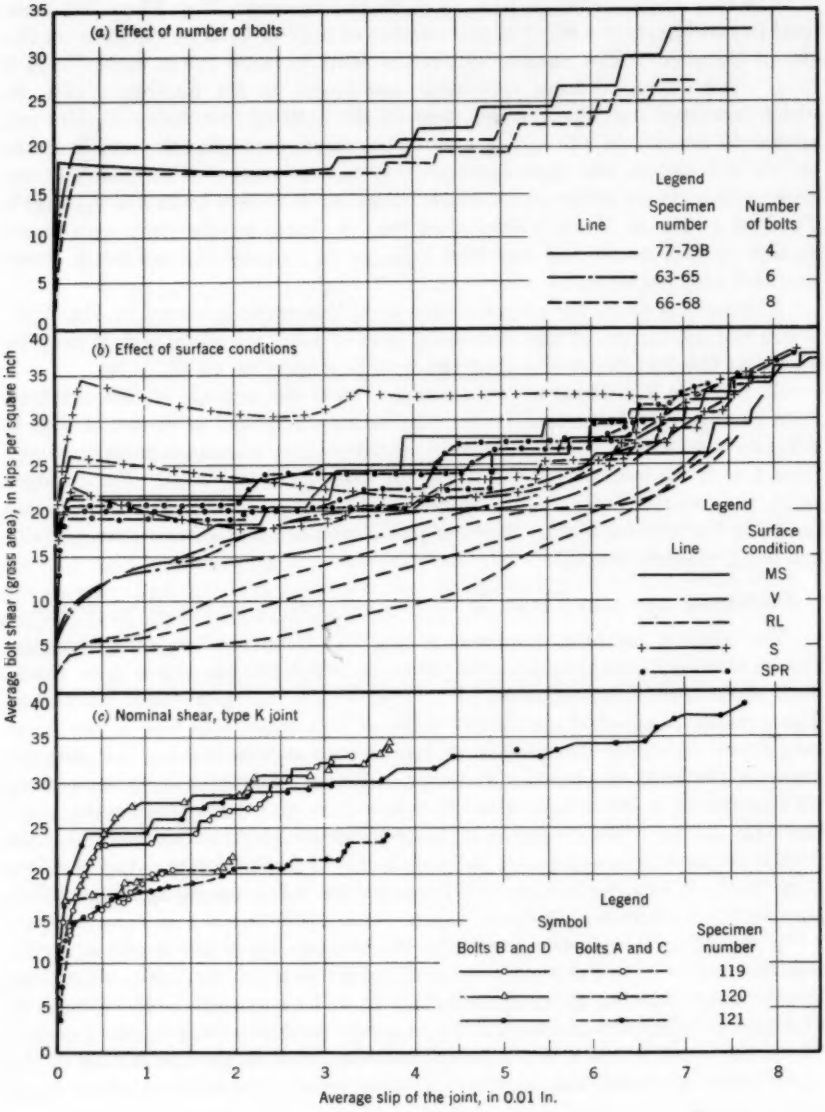


FIG. 10.—RELATION BETWEEN BOLT SHEAR AND SLIP

The tension in the test bolts was approximately 45 kips per bolt. Except as noted in the legend of Fig. 10(*b*), all bolt holes were drilled. The faying surfaces were prepared as previously described (Table 1).

Fig. 10(*b*) shows the shear-slip curves for this series of tests. The different manner in which slip occurred in the joints with painted faying surfaces as compared to those with mill-scale or sandblasted faying surfaces has been described and may also be seen in this figure, which shows the greatly reduced resistance to slip for which these coatings are responsible. Specimens with red lead paint on the faying surfaces developed less resistance to slip than did those with varnish. Because there was no definite point of first major slip and because the distance of slip depended on the period of application of a given load—even for light loads—there was no point even at low values of the bolt shear that could be termed the shear at first major slip.

The average shear stresses developed on the bolts at first major slip were 21.4 kips per sq in., 27.8 kips per sq in., and 20.0 kips per sq in. for specimen Nos. 13 to 15B with mill-scale faying surfaces, specimen Nos. 54 to 56 with sandblasted faying surfaces, and specimen Nos. 74 to 76 with subpunched and reamed holes, respectively. Thus, joints with drilled holes and those with subpunched and reamed holes developed approximately the same shear stress on the bolts at first major slip. Sandblasting the faying areas resulted in an increase in the resistance to slip.

The results of the tests of joints with painted surfaces were so unfavorable that painted faying surfaces are not recommended for bolted joints where slip is undesirable unless the ability of the paint in question to resist shear adequately can be demonstrated. Such a demonstration should subject the test joint to a load sustained for at least four hours to assure that the amount of slip would not increase with time.

A program of tests of joints sustaining loads for long periods of time is in progress (1952). The faying areas of these joints will be coated with various paints and rust preventatives.

Slip of Bolted Joints Under Other Types of Loading

Compression Joints.—The effect of tensile and compressive loadings on slip was compared in tension specimen Nos. 77 to 79B and compression specimen Nos. 104 to 106. The average shear stress developed on the bolts of the tension joints at first major slip was 18.2 kips per sq in. and on the compression joints was 20.3 kips per sq in. Because of the considerable scatter in the test results of bolted joints, it is reasonable to expect identical joints loaded in either tension or compression to develop approximately equal resistance to slip.

Torsion Joints.—The effect of combined torsional and compressive loading on slip was compared in specimen Nos. 104 to 106, specimen Nos. 119 to 121, and specimen Nos. 122 to 124, in which the eccentricity of the applied load with respect to the center of gravity of the rivet group was 0, 8 in., and 16 in., respectively. Fig. 10(*c*) shows the shear-slip curves for the joints with an eccentricity of the load of 8 in. The nominal shear on the bolts as defined for these tests was computed on the basis of the Gullander method[8] for com-

[8] "Structural Design," by H. Sutherland and H. L. Bowman, John Wiley & Sons, Inc., New York, N. Y. 1938, p. 73.

puting the shear in rivet groups with an eccentric load. The average computed bolt shear stress and the average measured slip used in this plot were those of the two bolts with the maximum computed nominal shear stress and maximum measured slip. The general pattern of behavior in the joints under torsional loading was similar to that in the tension and compression joints. Moreover, on the bolts under maximum shear, the average shear stress at first major slip of 25.1 kips per sq in. for a load eccentricity of 8 in. and 21.7 kips per sq in. for 16 in. compared favorably with the value of 20.3 kips per sq in. in the axially loaded joint. Although insufficient tests were made to establish a definite conclusion, it would appear feasible to apply the Gullander method to the design of eccentrically loaded bolted joints.

Conclusions

The results of the writers' research seem to justify the following conclusions with respect to the types of bolted joints tested in this investigation:

1. The prevention of appreciable slip by the use of properly tightened high-strength steel bolts is both possible and practicable.
2. For most of the joints, the shear stress on the gross area of the bolts at first major slip for joints with mill-scale faying surfaces was developed when the average stress on the net section of the joint was equal to, or slightly greater than, one half the upper yield-point stress of the plates.
3. Increasing the bolt tension beyond 36 kips caused no significant increase in the resistance to slip of the bolted joints, so long as the average stress on the net cross section at first major slip was less than from 16 kips per sq in. to 18 kips per sq in., or less than half the upper yield point of the plate steel. On the contrary, if the minimum stress on the net cross section at first major slip was greater than from 16 kips per sq in. to 18 kips per sq in., an increase of the bolt tension caused an increase of the frictional resistance of the joints; the stress required for a balanced design, with a tension-shear ratio of 1.00:0.75, would be in this higher range.
4. Properties of the joints such as the lap-plate thickness, the faying area, and the bolt pattern did not appear to have any important effect on the shear developed on the bolts at first major slip.
5. The few tests made of torsion joints indicated that it is feasible to apply the Gullander method to the design of eccentrically loaded joints.
6. Painted faying areas are not recommended for bolted joints unless the ability of the paint in question to resist shear adequately can be demonstrated: Red lead paint and varnish did not give satisfactory performance in these tests.

Further tests (1952) are required before adequate data on bolted joints under static loads will be available.